

A Wideband 220 GHz, 50 W Serpentine Waveguide Amplifier

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Abstract—Final assembly is underway for a 220 GHz, 50 W serpentine waveguide vacuum electron amplifier showcasing a novel embedded monofilament microfabrication technique based on UV-LIGA. Three microfabricated circuits from the same wafer exhibited matching frequency response characteristics. Cold testing of the beryllia vacuum windows shows bandwidth in excess of 25 GHz. A demonstration of the tube is expected by the end of 2012.

I. INTRODUCTION AND BACKGROUND

ULTRAVIOLET photolithography techniques along with copper electroforming (collectively, UV-LIGA) are being developed at the U.S. Naval Research Laboratory in order to span the spectrum from under 100 GHz through 1 THz [1-2]. With use of a Patent-Pending embedded polymer monofilament UV-LIGA technique [3], 3D all-copper structures have been demonstrated that allow arbitrarily small beam tunnels to be fabricated to arbitrary length along with slow-wave amplifier circuits. These techniques have been demonstrated at W-band (95 GHz), G-band (220 GHz), and 670 GHz to date. These frequencies provide jam-proof communication links and high resolution imaging by virtue of the inherently short wavelengths [4].

II. AMPLIFIER STATUS

This serpentine waveguide (SWG) amplifier is designed to operate from a single, round 11.7 kV, 120 mA electron beam; other design parameters are listed in Table I. Figure 1 shows the final brazed body assembly of the tube along with the cold test setup. Figure 2 shows the predicted gain curve in MAGIC 3D producing 18 dB small signal gain with a 15.5 GHz bandwidth [5-6]. Windows made from BeO are predicted to yield a -30 dB reflection over a 20 GHz bandwidth. Using a CPI 5W EIK amplifier as a driver, over 60 W output power is expected from the tube.

III. CIRCUIT FABRICATION

To create reliable, high vertical aspect ratio serpentine features as required, a UV-LIGA technique was employed in two layers (Figure 3). The second layer made use of polymer monofilaments embedded in the SU-8 photoresist in order to hold the shape of the electron beam tunnels while the ultraviolet passed through a lithographic mask to create the serpentine patterns [7-8].

TABLE I: Amplifier Operating Parameters

Beam voltage	11.7 kV
Beam current	120 mA
Beam tunnel diam	190 μ m
Small Sig. Gain	18 dB
Bandwidth	15.5 GHz
Max Power Out	63 W
Number of gaps	64

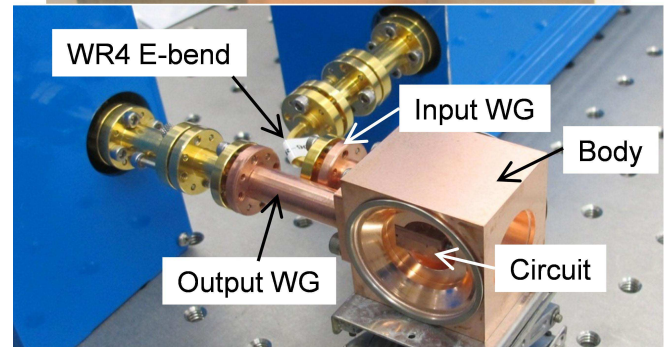
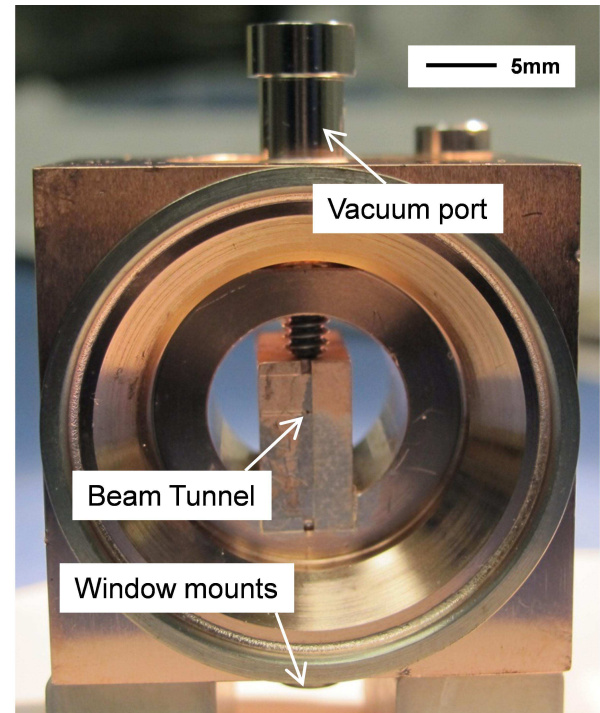


Figure 1. (Top) Final brazed body assembly. (Bottom) Pre-braze assembly under cold test from 140 GHz to 325 GHz.

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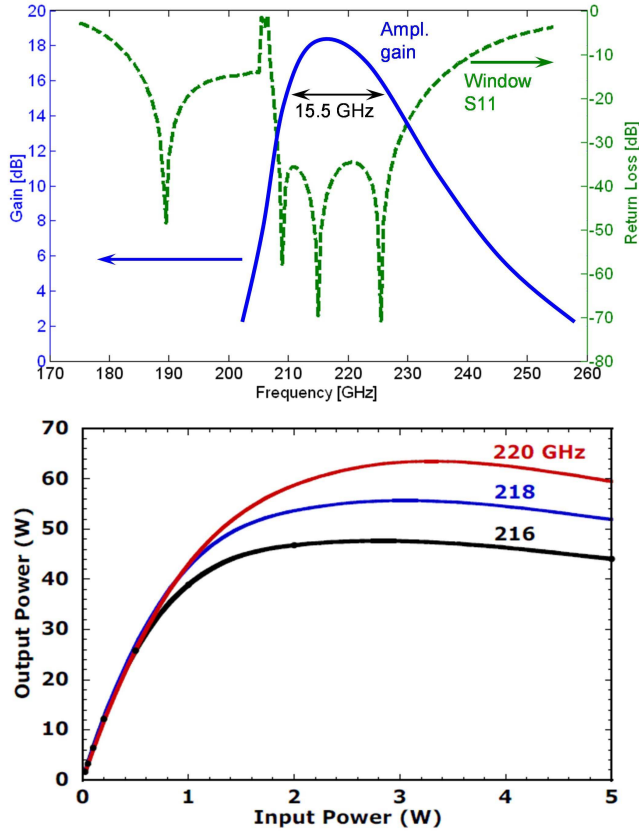


Figure 2. (Top) MAGIC 3D Prediction of amplifier performance (solid) and HFSS prediction of window performance (dashed). (Bottom) Drive curve prediction in MAGIC 3D showing over 60 W output power at 220 GHz.

After the SU-8 molds have been formed around the polymer filament, the wafer is placed in an electroforming bath to deposit copper. The wafers are ground to thickness and polished, followed by a molten salt bath to remove the SU-8 [7]. After dicing to size and final lapping to thickness, the circuits are completed by brazing a flat cover piece on top. Figure 4 shows various features of a good circuit both before and after brazing.

IV. COLD TESTING

The most important part of the microfabrication process is cold testing the circuits and windows to ensure they were fabricated correctly. Using vector network analysis covering G- and H-bands (140-220 GHz and 220-325 GHz), the circuits are fully characterized, including pertinent stopbands near 300 GHz. During the cold testing, however, stopbands began appearing right in the operating band around 220 GHz. These stopbands can easily lead to oscillation since the electromagnetic waves cannot penetrate through the circuit. Figure 5 compares several circuits with varying degrees of stopbands at 220 GHz. It became apparent that slight misalignment of the beam tunnel in the planes of the serpentine variation breaks periodicity into a bi-periodic-like structure, which opens a new stopband at the point in the

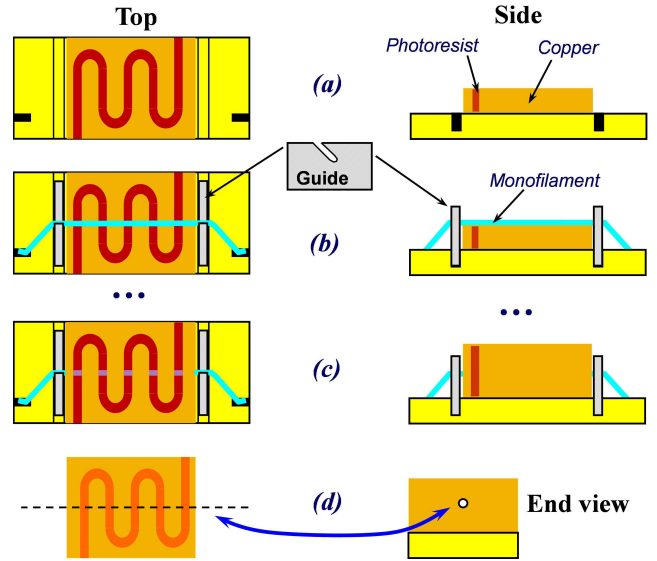


Figure 3. Two-layer embedded polymer monofilament method. (a) The first layer of the circuit is produced by UV-LIGA with the photoresist left behind in the electroformed copper, which is ground and polished to the desired thickness, (b) the monofilament is fixed in place over the first layer, (c) the UV-LIGA process is performed again to create a second layer on top of the first with the monofilament buried inside, (d) dicing to size and the removal of the monofilament and photoresist completes the structure. Beam tunnel location shown by dotted line

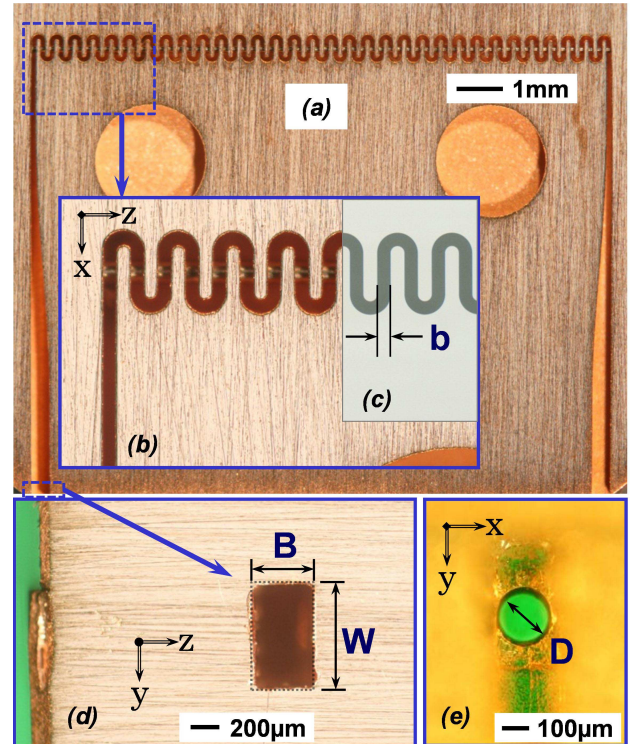


Figure 4. (a) Photo of SWG circuit with beam tunnel prior to brazing a flat cover on. Shown with 0.0072 inch diameter gage pin inserted through beam tunnel. (b) Zoom in view of circuit with the gage pin shown inserted, (c) view of the ideal mask pattern, (d) view of input waveguide in completed circuit after brazing, (e) view of beam tunnel hole on brazed circuit showing a clean hole by green backlighting.

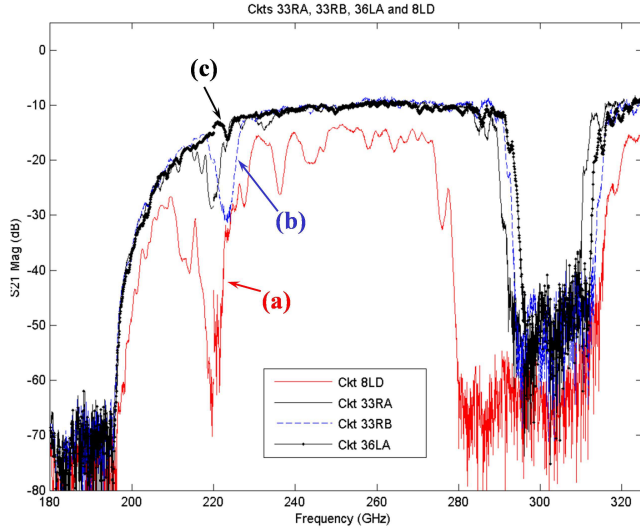


Figure 5. (a) Early circuit with significant misalignment on the order of a beam tunnel radius shows a severe stopband at 220 GHz, (b) improved alignment, but still showing strong stopbands, (c) two-layer approach with very good alignment corrects the problem.

structure where the phase advance per period is $3\pi/2$. Since the π -point is cutoff around 196 GHz, and the 2π -point is a stopband around 290 GHz, about half-way in between ($3\pi/2$) yields the widest bandwidth and is thus chosen as the operating point for the design. Therefore, beam tunnel misalignment can cause stopbands to appear right around the operating point. The solution is better beam tunnel alignment. Figure 5(a) shows an early circuit with bad beam tunnel misalignment on the order of a beam tunnel radius. Figure 5(b) shows reduced alignment error on the order of one-fifth of the beam tunnel radius, still resulting in stopbands over 15 dB deep. Finally, a two-layer fabrication approach allowed the misalignment to be reduced to under 5 microns (5% of a beam tunnel radius), resulting in a nearly irrelevant bump of under 2 dB, as in Figure 5(c).

Six circuits were removed from one wafer (#36), of which three are shown in Figure 6 exhibiting an excellent match in frequency response characteristics. These three circuits are from different locations on the same wafer and their beam tunnels were fabricated on different filament strands, indicating the technique is highly repeatable and precise.

V. VACUUM WINDOWS

The beryllia vacuum windows are discs that are half-wave resonant pillboxes contained inside of TE_{10} mode rectangular to TE_{11} cylindrical transitions [9]. Figure 7(a) shows a cross section of this geometry, and Figures 7(b) and 7(c) show an actual beryllia disc brazed into a copper barrel. The length of the barrels is critical in obtaining the correct phase cancellation in the cavity for low overall reflectivity. The barrels were therefore machined slightly longer than the design so that they could be individually tuned in to compensate for slight variations in window thickness.

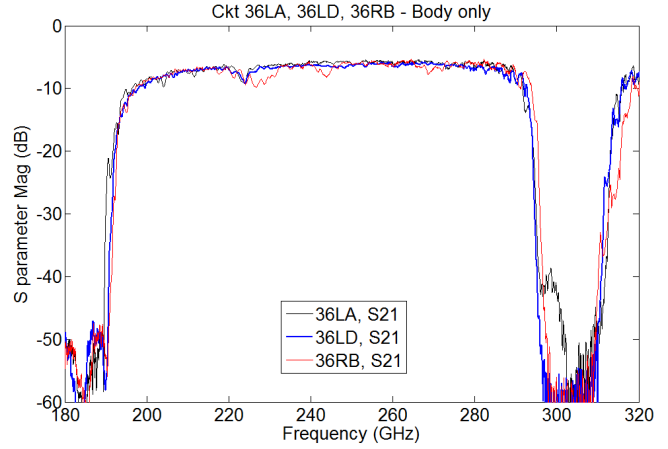


Figure 6. Comparison of S_{21} measurements of three circuits from wafer #36 exhibiting excellent match in frequency response. Note: S_{21} values shown include 2.5 dB of total losses in external tapers and waveguides.

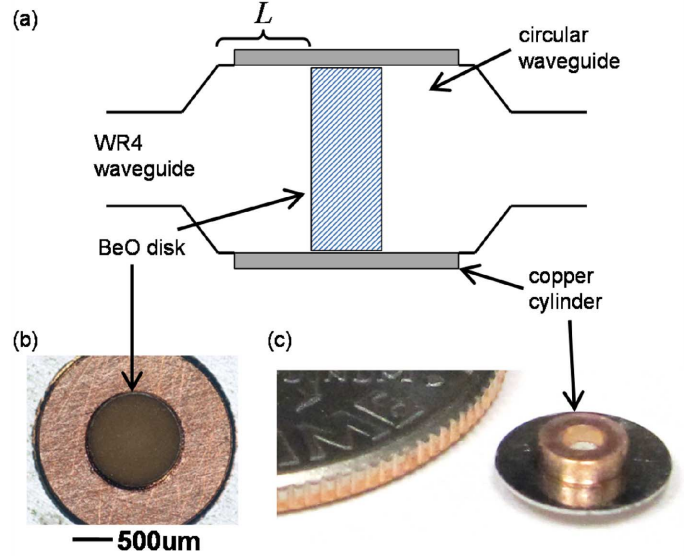


Figure 7. (a) Geometry of pillbox window. Taper mode converters transition between TE_{10} rectangular guide and circular guide. The circular waveguide length on one side of the window disk is L . (b) Optical micrograph of a brazed window assembly at 50x magnification. (c) Photograph of window assembly next to a U.S. dime.

Figure 8 shows how the output window measured at various stages of lapping. When tuned in, the window can be seen to improve from a few narrowband resonances around 230 GHz to a broad bandwidth of over 25 GHz with a reflection below -20 dB. The insertion loss of the windows, along with that of the waveguides, waveguide tapers, and circuit, are tabulated in Table II. The window insertion losses are below 0.1 dB at 220 GHz. The cold loss of the circuit is consistent with simulations involving copper with an effective conductivity half that of the ideal, DC conductivity value.

The windows were tested at 218.4 GHz at 2.5W CW using a CPI model VKY2444 EIK amplifier capable of 5W

CW output power. No breakdown, arcing or heating was observed.

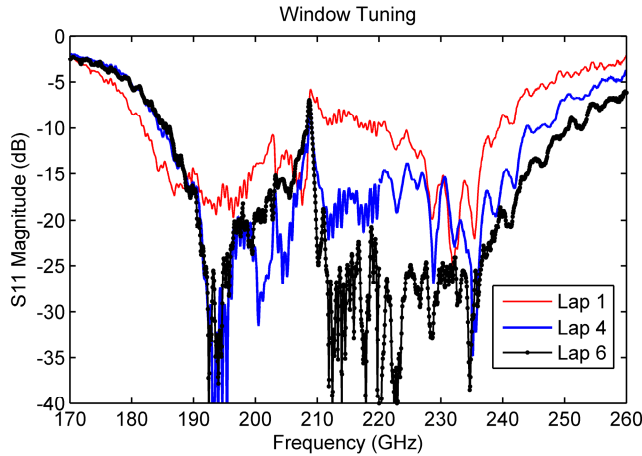


Figure 8. S_{11} measurement of output window at various stages of lapping the barrel length down to tune it in. Greater than 25 GHz of bandwidth is achieved at below -20 dB S_{11} .

TABLE II. Loss Budget

Component	Cold Loss
W/G, WR4 E-plane bend	0.6 dB
Input W/G, 0.75"	0.3
Input Window	<0.1
Body Input Taper	0.4
Circuit	4.4
Body Output Taper	0.4
Output Window	<0.1
Output W/G, 1.5"	0.6
TOTAL COLD LOSS	6.9 dB
TOTAL W/G LOSS	2.3 dB

VI. FINAL CIRCUIT COLD TESTING

Figure 9 shows the final S_{21} measurements of the three good circuits including the tuned windows, tapered waveguide in the body, and external waveguides. There is a small stopband of around 2 dB near 223 GHz, but it is not predicted to cause oscillations due to its small magnitude.

VII. SUMMARY

Successful 220 GHz amplifier circuits have been created using a Patent-Pending two-layer UV-LIGA technique with embedded polymer monofilaments. Circuits were created with exceptionally high yield for this frequency range, and the techniques are being applied to cover the spectrum from below 100 GHz to over 1 THz. Vacuum tight, wideband beryllia windows were successfully fabricated and tuned in to achieve over 25 GHz of bandwidth with better than -20 dB reflection. The circuits, tube body and window assemblies were successfully brazed and await final integration with the electron gun, collector and magnet system. Full demonstration testing is expected to commence by the end of 2012.

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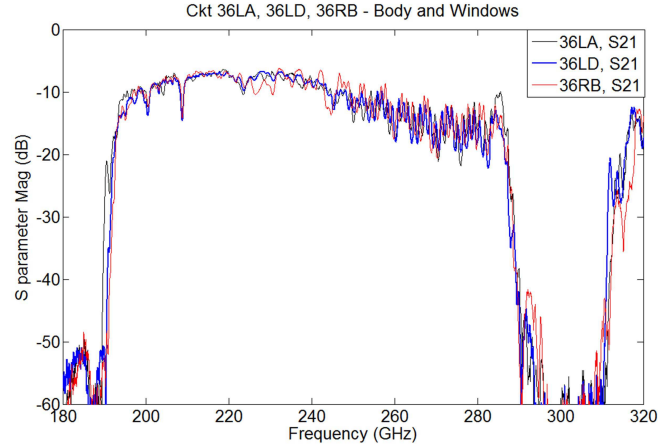


Figure 9. Cold test S_{21} measurements of three circuits mounted in the final body along with the vacuum windows prior to braze. Note: S_{21} values shown include 2.5 dB of total losses in external tapers and waveguides.

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